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THE CROSSED-FIELD CLOSING SWITCH-A STATUS REPORT

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November 1978

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THE CROSSED-FIELD CLOSING SWITCH – A STATUS REPORT*

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Abstract

The crossed-field closing switch (CFCS) has been evaluated using a modulator consisting of 25 cables each 15.24 m long. A low-inductance 2-Ω copper sulfate load was used to terminate the modulator in its characteristic impedance. Before evaluating the CFCS in the cable modulator, studies were made of firing characteristics and mode of operation using a conventional pulse forming network of 0.5 Ω impedance matched to a copper sulfate load. The pulse width was a nominal 12 μs. Preliminary results were then obtained with the cable modulator at an anode voltage of 23 kV at a peak current of 6 kA and pulse repetition rates up to 500 Hz. The pulse width, measured at the half power points on the load, was 160 ns. Experimental results are shown for the cable modulator test, and the dependence of operating mode on circuit parameters is discussed.

Previous Results

The CFCS operates reliably at average power up to 0.8 MW at pulse repetition frequencies up to 108 Hz.[1-4] Repetitive switching at peak current levels of 20 and 40 kA at an anode voltage of 40 kW was demonstrated using a line-type modulator. The initial experimental set-up is shown in Figure 1, which also includes an oscilloscope trace showing the peak current waveform generated at an anode voltage of 40 kV. (The vertical sensitivity is 20 kA/div and the horizontal sweep is 2 μs/div.) The trace consists of approximately 16 pulses from a train of 2400 pulses in a 30 s run.

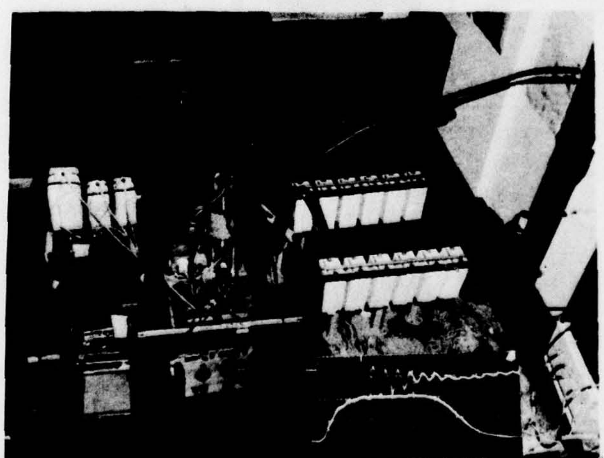

Figure 1. Initial Experimental Setup (1976)

Subsequently, the CFCS was tested in another line-type modulator of similar total impedance (1 Ω) and pulse width (12 μs) in which the current rise time (10 to 90%) was reduced from 2 to 1 μs. Peak currents of up to 47 kA were switched at average currents up to 40 A using burst lengths of a few seconds at the higher average power loadings. In general, however, the reliability was considerably reduced over that experienced in the initial phase of the evaluation. Anode voltage hold-off capability and pulse-to-pulse jitter were noticeably influenced by the operating mode, which was found to be related to peak B field value, anode voltage, and gas pressure. Unfortunately, the evaluation was somewhat clouded by an eccentricity in the grid cathode spacing (which was accidentally introduced during the refurbishing of the CFCS after the initial evaluation phase) and by the presence of several high-frequency resonances in the test circuit. To establish the circuit independent characteristics of the CFCS, a cable modulator system was constructed. This allowed examining the trigger characteristics more carefully.

Short Pulse Characteristics

Test Circuit

The circuit chosen for short pulse length operation included: a variable impedance pulse forming network (PFN) composed of 50 ft (15.24 m) lengths of RG 214/U cable, a set of low-inductance collector plates for connection to the CFCS, a matching set of load cables 15 ft (4.57 m) long, and a low-inductance $CuSO_4$ load.[6] Figure 2 shows these basic components as they were arranged in the laboratory at the Evans area of Ft. Monmouth. The PFN was draped from the ceiling to the CFCS at one end and to a groundable common terminal at the other. To date, only 25 of the possible 50 cables have been connected. This yields a 2-Ω system.

A detailed drawing of the circuit is shown in Figure 3. The inductances shown are estimated from the known geometries, and the 77-pF capacitor is the calculated internal capacitance of the CFCS. The CFCS cathode was chosen for the system grounding point. The locations A and B were the collector plate voltage sensing points, and a current transformer (CT) was normally located as shown to sample a fraction of the load current.

The calculated cable signal reflection times are 154 and 46 ns for the PFN and load cables, respectively. The PFN was charged both resistively and resonantly (as shown).

Calibration

A Tektronix 7834 400 MHz storage oscilloscope was used to record the data. The CT was a Pearson 410 with

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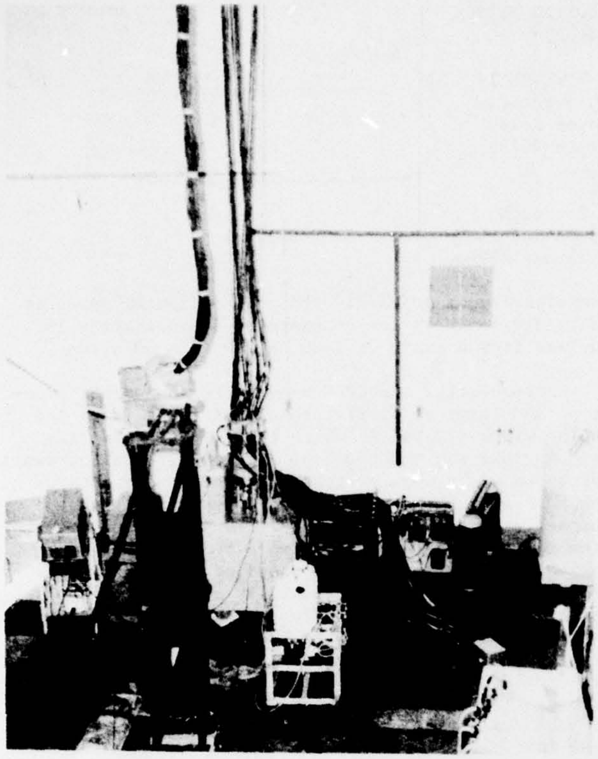

Figure 2. Experimental Arrangement

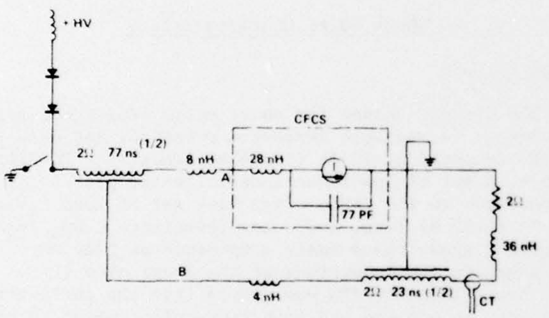

Figure 3. Test Circuit

a rated rise time of 10 ns and a 0.1 V/A output. Current transformers with higher ratios were found either to not have their rated rise time capability or to introduce too much stray inductance into the circuit being monitored to be of any use. The Pearson 410 was of marginal use. The voltage probes were Tektronix 6015s (20 kVDC, 1000:1) with 5 ns rise times.

The system response was checked at low voltage by mechanically shorting out the CFCS at point A. Figure 4(a) shows the current measured at the anode (lower trace) and the voltage measured at point B (upper traces) at 50 ns/div. The voltage noise may be pick-up noise or the natural ringing frequency of the CFCS internal capacitance.

The trapezoidal current pulse appears to have a linear 50 ns rise and a similar fall. The pulse width is about 175 ns. The fact that the top is not flat is related to the CT primary leakage inductance. Figure 4(b) shows the dramatic change in the signal (upper trace) when the CT is moved to its normal location on two of the load cable connections. The sharp features of the pulse are now washed out in the noise.

The location of the lead cables had a strong effect on the signal waveforms. Some noise coupling to the horizontal amplifier was observed at high-voltage operation. Taken collectively, this noise problem presently restricts any interpretation of the subtle features of the high-voltage data to a qualitative nature.

Magnetic Field and Grid Pulsers

The magnetic control field was generated by a resonantly charged thyratron pulser delivering a 60 A sinusoidal pulse with a 410 μs half period to the 100 turn field coil. The limiting frequency of this particular pulser was about 500 Hz.

The grid pulser waveforms are shown in Figure 5. The upper trace is the current (which was set to reach a peak of 80 A). The grid voltage reaches a peak of 4 kV and then drops to about 300 V on the onset of conduction. The grid was delayed in time with respect to the magnetic field pulse. This delay was variable. The pulser voltage was not changed during these experiments, although a 0.01-μF peaking capacitor was sometimes added from the grid terminal to ground.

Trigger Timing

The details of the trigger characteristics of the triode CFCS are beyond the scope of this paper. However, recent experience with low-impedance circuits has shown that the present CFCS design may be operated reliably and with low jitter. Certain precautions

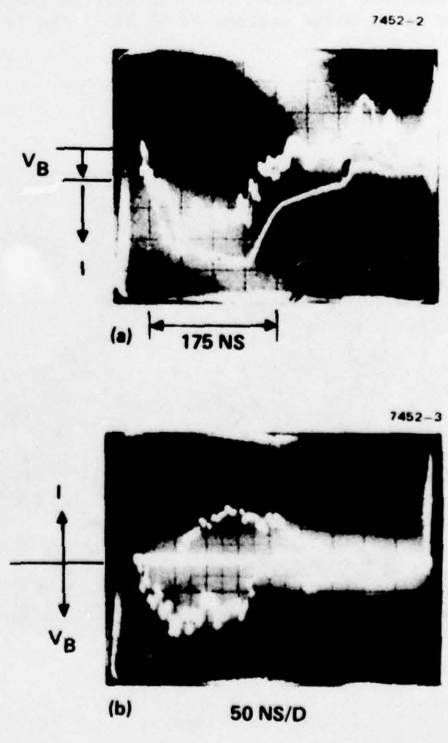

Figure 4. Low Voltage Calibration

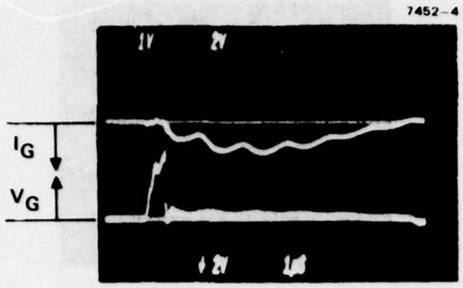

Figure 5. Grid Pulse Waveforms

must be taken to maintain a well defined operating point in parameter space to achieve this result. If one variable is altered, another must typically be changed to compensate. The critical variables in this parameter space are anode voltage, magnetic field strength, gas pressure, and grid timing.

Without pressure control, and using the magnetic field pulse trigger signal as a reference, we were able to achieve a stability of about ±10 ns in the anode fall point (some 200 µs later), during runs of about 700 pulses. This jitter level includes variations in the grid pulser and delay circuitry. A further reduction could be achieved by referencing the grid voltage signal.

Single Pulse Experiments

Figure 6 shows the load current waveform at a charging voltage of 10 kV. The peak current is 2.5 kA with a pulse shape equivalent to the calibration pulse shape of Figure 4(a), but without the asymmetrical distortion produced by the CT inductance. The pulse width is 165 ns, which is consistent with the 154 ns theoretical PFN pulse width and the sensor rise times (∿ 10 ns). The mismatch at the end of the pulse is probably due to the load inductance.

The anode voltage fall (measured at point A) appears to be a function of gas pressure. The initial fall is often seen at low pressure to have a gradual drop in the beginning, followed by a more rapid exponential fall. This is shown in Figure 7 at 37 mTorr of He. When the pressure is increased, the initial fall component disappears and the drop is precipitous. This is shown in Figure 8 at 50 mTorr. (Here the noise in the horizontal amplifier is most evident, negating any attempt to assign an anode fall time at this sweep speed.)

The anode fall time may be inferred by examining the foot of the current pulse rise. Any delay in fall

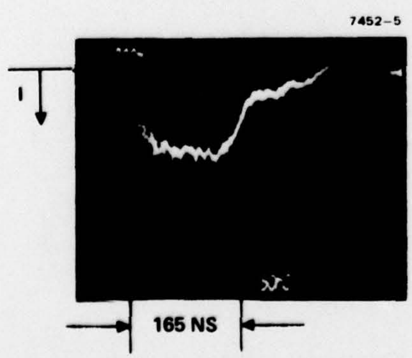

Figure 6. Load Current Waveform

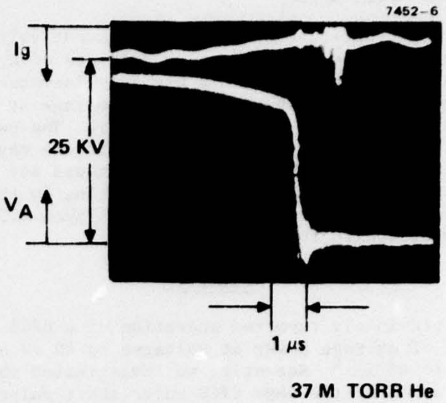

Figure 7. Anode Fall at Low Pressure

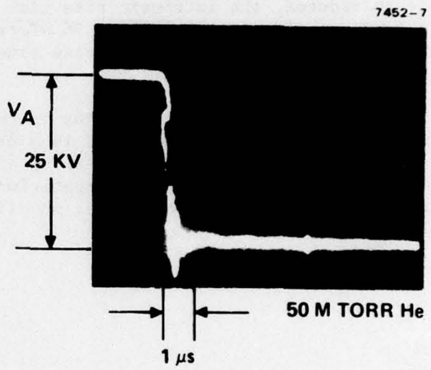

Figure 8. Anode Fall at Intermediate Pressure

would show as a precurrent. Figure 9 shows both the anode fall and the load current at 50 ns/div and at a pressure of 75 mTorr. No significant prepulse is visible. The base of the anode fall exhibits a decaying time constant of about 15 ns (exponential). This is mostly accounted for by assuming that 5 ns is due to the probe response and that the L/2R circuit time constant is 7 ns. The remainder is well within the systematic error.

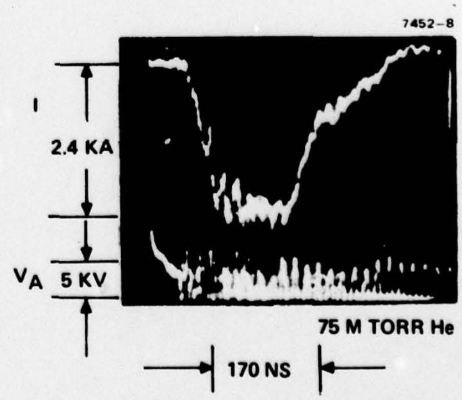

Figure 9. Anode Fall at High Pressure

Repetitive Operation

During repetitive operation, the anode voltage was set to 22 kV, resulting in peak currents of about 5.5 kA. The repetition rate was then increased to 526 Hz. Figure 10 shows the anode voltage at 10.5 kV/div using a resistive divider. The sweep speed is 1 ms/div. The upper trace is the magnetic field waveform. (The frequency limit was set by the magnetic field pulser thyratron latching in the on state.) The peak average current was then 0.5 A with 5.4 kW delivered to the load.

Summary

We previously reported operation of a CFCS at over 800 kW of average power at voltages to 40 kV and currents to 40 kA.[4] Recently, we investigated the characteristics of the same CFCS under short pulse duty. The device is presently inductively limited to rise times of 50 ns. The intrinsic rise time of the device (i.e., avalanche time) is $\lesssim$ 10 ns at pressures approaching its Paschen limit ($\sim$ 75 mTorr). As the pressure is reduced, the intrinsic rise time increases until a 1-μs prepulse is observed at 36 mTorr. Jitter times vary along with the intrinsic rise times and are of the same order of magnitude.

The CFCS has been run at over 500 Hz in the short pulse mode. Conduction appears to be in a crossed-field glow discharge. Therefore, previous simulations[1,5] suggest that the ultimate repetition rate will be limited only by the auxiliary power supplies and thermal cooling.

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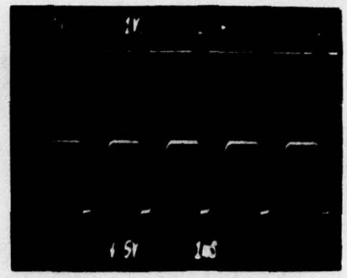

Figure 10. Operation at 526 Hz

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